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BASIC INSTABILITY MECHANISMS IN CHEMICALLY REACTING
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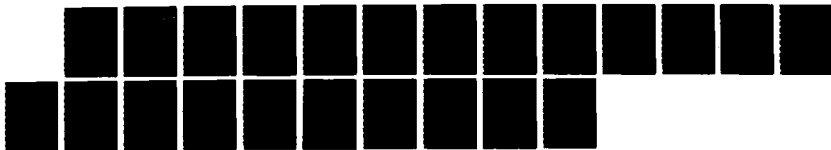
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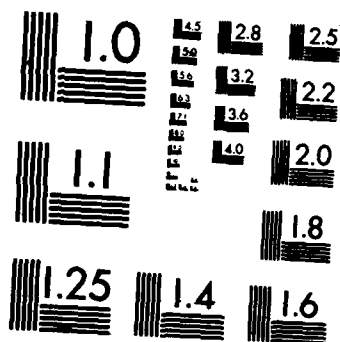
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Basic Instability Mechanisms
in Chemically Reacting Subsonic and Supersonic Flows

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Massachusetts Institute of Technology

Summary of Progress

Simultaneous measurements of velocity (in a direction normal to the flame brush) and temperature in premixed, rod-stabilized, lean methane/air V-flames demonstrated the presence of high-frequency fluctuations within slowly drifting flame brushes, thus indicating a structure different from that of a simple wrinkled-laminar flame. Both the velocity and the temperature fluctuations gave maximum RMS values at a position somewhere between the unreacted and the product gases. Furthermore, cross-correlation coefficients of these simultaneous signals assumed rather high values within the reaction zone, suggesting the possibility that these fluctuations might be induced by the same governing mechanism (which, according to the theory reported previously, was due to the coupling between chemical kinetics and turbulence).

A paper on the genesis of transverse waves in gaseous detonations was published in Combustion and Flame. A manuscript on the thermal structure of turbulent flames was submitted for presentation at the Fall Technical Meeting

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of the Eastern Section of the Combustion Institute. Another manuscript on turbulence-combustion interactions was in preparation.

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I. Objectives and Scope of Work

The main objectives of this research are to determine and elucidate major mechanisms governing turbulence-combustion interactions in different spectral regimes and to provide sound basis for formulating guidelines for improving combustion efficiency and reducing emissions. During the past year, simultaneous velocity and temperature fluctuations in premixed, rod-stabilized, lean methane/air V-flames were examined. High-frequency fluctuations were found within slowly drifting flame brushes, thus indicating a structure different from that of a simple wrinkled-laminar flame. Furthermore, cross-correlation coefficients of these simultaneous signals assumed rather high values within the reaction zone, suggesting the possibility that these fluctuations might be induced by the same governing mechanism (which, according to the theory reported previously, was due to the coupling between chemical kinetics and turbulence).

A paper on the genesis of transverse waves in gaseous detonations was published in Combustion and Flame. A manuscript on the thermal structure of turbulent flames was submitted for presentation at the Fall Technical Meeting of the Eastern Section of the Combustion Institute. Another manuscript on turbulence-combustion interactions was in preparation.

II. Results and Discussion

In order to understand the mechanisms governing turbulence-combustion interactions, it is essential to examine cross-correlations of fluctuations in velocity and scalar quantities, such as temperature, density, pressure,

and species concentration. To measure the velocity fluctuations, a one-component Laser-Doppler-Velocimetry (LDV) system (Model 9100-6) was purchased from TSI with the support of a DoD-University Research Instrumentation Grant. The LDV system was installed, tested, and used (together with frequency-compensated fine-wire thermocouples) to examine simultaneous velocity (in a direction normal to the flame brush) and temperature fluctuations in premixed, rod-stabilized, lean methane/air V-flames. Some of the results are presented below.

Similar to the temperature fluctuations noted in our earlier experiments, high-frequency velocity fluctuations were also observed within slowly drifting flame brushes. Figure 1 shows a segment of the simultaneous all-pass velocity and temperature signals, together with the corresponding "instantaneous" mean velocities and temperatures computed within 25-ms time intervals* and 20-Hz low-pass signals. Both of these fluctuations gave maximum RMS values at a position somewhere between the unreacted and the product gases. As shown in Figure 2, the maximum apparent RMS temperature fluctuations (over time intervals much longer than the characteristic time of the low-frequency flame drifting) was 240 K instead of 700 K, should the flames be simply wrinkled discontinuities. Similarly, the maximum apparent RMS velocity fluctuations was 0.15 m/s instead of 0.45 m/s.

Figure 3 shows the high-frequency RMS temperature and velocity fluctuations on the basis of the respective "instantaneous" mean values

*The characteristic time for low-frequency drifting was approximately 200 ms, as deduced from previous dual-thermocouple measurements.

within 25 ms. Again, maximum RMS values occurred at positions somewhere between the unreacted and the product gases. Furthermore, the RMS values for a flame in the presence of a 10-mesh turbulence-generating grid at the burner exit (TF10) were higher than those in the absence of any turbulence-generating grid (quasi-laminar or QL), except an opposite trend seemed to be present for RMS velocity fluctuations near the reacted region. These findings are all consistent with the postulation that the high-frequency fluctuations are induced through coupling between chemical kinetics and turbulence.

Figure 1 also shows a comparison of the "instantaneous" mean values with the corresponding 20-Hz low-pass signals. Their close agreement seemed to imply that the RMS values shown in Figure 3 pertained to frequencies higher than 20 Hz.

Normalized cross-correlation coefficients of the simultaneous velocity and temperature fluctuations are also shown in Figures 2 and 3, together with the corresponding RMS values. They remained positive within the entire flame brush, thus indicating the inappropriateness of the gradient model to account for the turbulent energy transport (in agreement with the prediction near the unreacted region from a previous theoretical study on the evolution of fluctuations in a reacting shear layer). Both the apparent (cf. Figure 2) and the "instantaneous" (Figure 3) $V'-T'$ cross-correlation coefficients assumed rather high values (0.8-0.9, maximum) within the reaction zone, suggesting the possibility that these fluctuations might be induced by the same governing mechanism (which, according to the theory presented in previous reports,

was due to the coupling between chemical kinetics and turbulence).

The "instantaneous" mean velocities and temperatures within the flame brush were found to fluctuate at low frequencies as the result of the flame drifting across the signal-monitoring station. Should the flame be simply a wrinkled discontinuity, they would assume only values corresponding to the unreacted and the product gases. However, Figure 4 shows the existence of a turbulent structure, with the instantaneous velocities varying almost linearly with the instantaneous temperatures. Since the velocities were measured in a direction normal to the flame brush, this linear relationship was expected because the mass flux crossing the flame brush should remain the same.* As this mass flux was related to the local turbulent-flame-propagation speed, Figure 4 further suggested that the propagation speed increased by about 25 percent due to the presence of a 10-mesh grid at the burner exit.

Figure 5 shows the distribution of the apparent low-frequency RMS velocity and temperature fluctuations (over time intervals much longer than the characteristic time of the low-frequency flame drifting) for TF10 and quasi-laminar flames. Again, their maximum values (0.07 and 0.10 m/s or 140 and 190 K, respectively) were much less than the values (0.45 m/s or 700 K) expected from the wrinkled-laminar-flame model.

Figure 5 also shows the apparent normalized cross-correlation coefficients of the simultaneous low-frequency velocity and temperature fluctuations. Since these fluctuations were essentially induced by the

* Note that the density-temperature product was assumed to remain constant for almost the same pressure across the flame brush.

same mechanism (flame drifting), almost perfect correlation was observed in a major portion of the flame brush.

Spectral density distributions of mean-square temperature and simultaneous mean-square velocity fluctuations were examined for both TF10 and quasi-laminar flames. Figures 6 a and b show the comparison for the apparent all-pass mean-square values and Figures 7 a and b show the comparison for the "instantaneous" high-frequency mean-square values at a position within the flame brush where the RMS values were the maximum. In all cases, remarkable similarity was observed over the entire spectral regime between the velocity and the temperature fluctuations. Together with the earlier observation in Figures 2, 3 and 5 on the rather high values of the normalized cross-correlation coefficients, this spectral similarity gave further support to the postulation that both the velocity and the temperature fluctuations were induced by the same governing mechanisms.

Consistent with the comparison of the RMS values for TF10 and quasi-laminar flames in Figure 5 for the low-frequency fluctuations and in Figure 3 for the higher-frequency fluctuations, Figures 8 a and b show that the spectral density functions for TF10 were lower in the low-frequency regime and higher in the higher-frequency regime. Coupled with the observation from Figure 4 that the local turbulent-flame-propagation speed was higher for TF10, one might infer that this speed increase was possibly due to the presence of the small (or high-

frequency) eddies as suggested by Damköhler^{*}. Experiments are in progress to determine the turbulence scales responsible for the enhancement of the propagation speed and for the flame drifting by the use of two thermocouples at different relative orientations with respect to the LDV station.

As observed in Figures 2, 3 and 5, the RMS values were the maximum somewhere between the unreacted and the product gases. Comparisons of the spectral density distributions of apparent all-pass mean-square velocity fluctuations just upstream of the flame brush and at a position of maximum RMS values were shown in Figures 9 a and b for TF10 and quasi-laminar flames, respectively. A significant increase was observed across the flame brush in both cases.

Probability density functions (PDF) across the flame brush for the simultaneous temperature and velocity fluctuations were shown in Figures 10 and 11 for TF10 and QL, respectively. Near the unburned and the burned regions, the temperatures and the velocities corresponded essentially to those of the ambient and the products, respectively. Within the flame brush, however, significant contributions from intermediate states were observed. Even at the location of the maximum RMS values (denoted as 0 mm in the spatial coordinates), their shapes were not bimodal, confirming the earlier observation that the turbulent flame structure was not one of the simple wrinkled-laminar flame.

^{*}Damköhler, G. (1940). Der Einfluss der Turbulenz auf die Flammgeschwindigkeit in Gasgemischen. Z. Elektrochem. Angew. Phys. Chem. 46, 601; (1947). Engl. trans: The effect of turbulence on the flame velocity in gas mixtures. NACA Tech. Mem. 1112.

III. Publications and Reports

See attached Enclosure.

IV. Professional Personnel and Advanced Degree Awarded

Professor T. Y. Toong.

Z. Y. Du was awarded the degree of Master of Science, May 1985.

Thesis title: Instability Analysis in a Reacting Shear Layer.

V. Interactions

A presentation on Turbulence-Combustion Interactions — Theory and Experiments was made by T. Y. Toong at the 1985 AFOSR/ONR Contractors Meeting on Combustion on July 25, 1985 at the California Institute of Technology.

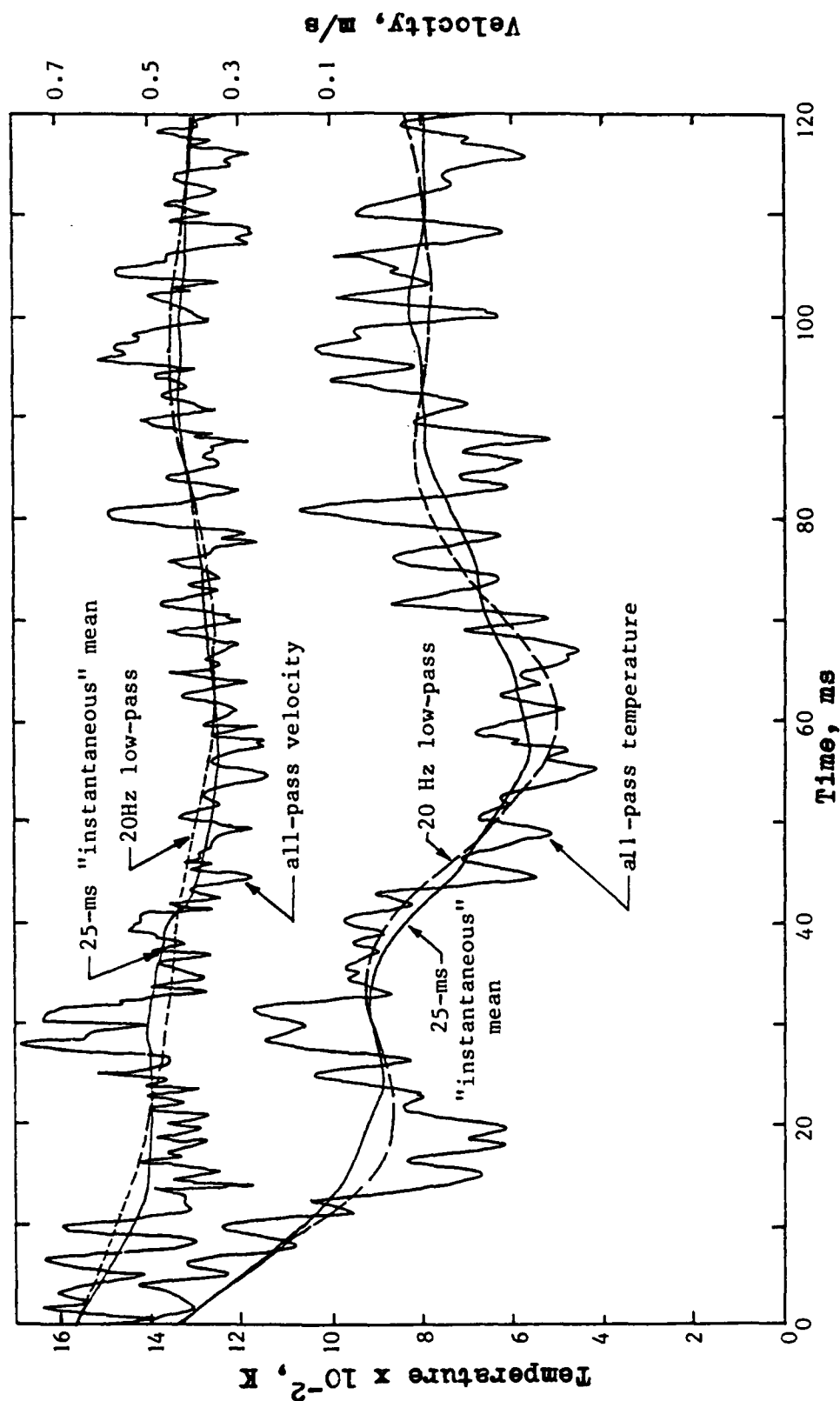


Fig. 1 Comparison of all-pass, "instantaneous" mean, and 20-Hz low-pass simultaneous velocities and temperatures.

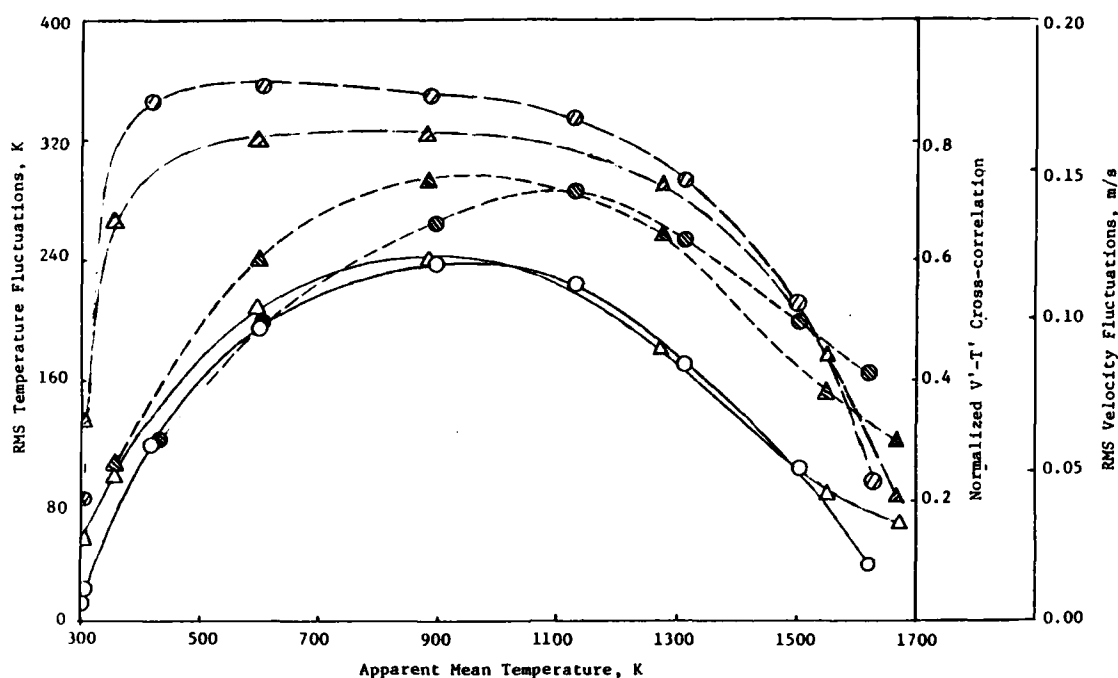


Fig. 2 Apparent RMS temperature, RMS velocity, and normalized $V'-T'$ cross-correlation coefficient versus apparent mean temperature. Triangle, with 10-mesh turbulence grid; circle, no turbulence grid. \circ, Δ RMS temperature; \odot, \triangle RMS velocity; \odot, Δ $V'-T'$ cross-correlation.

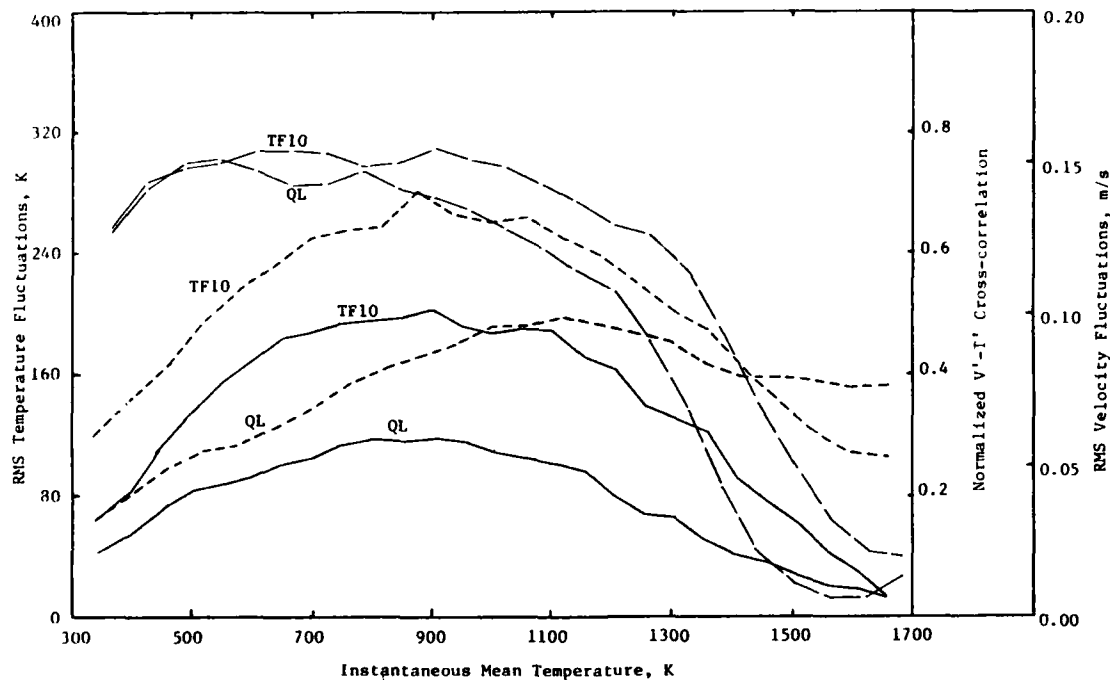


Fig. 3 Comparison of RMS temperature (solid lines), velocity (short-dashed lines) fluctuations, and normalized $V'-T'$ cross-correlation coefficient (longer dashed lines) within high-frequency region at different "instantaneous" mean temperatures. TF10, with 10-mesh turbulence grid; QL, no turbulence grid. Equivalence ratio, 0.75; mean mixture velocity, 2.4 m/s; 35mm downstream of 2.1 mm-diameter flameholder.

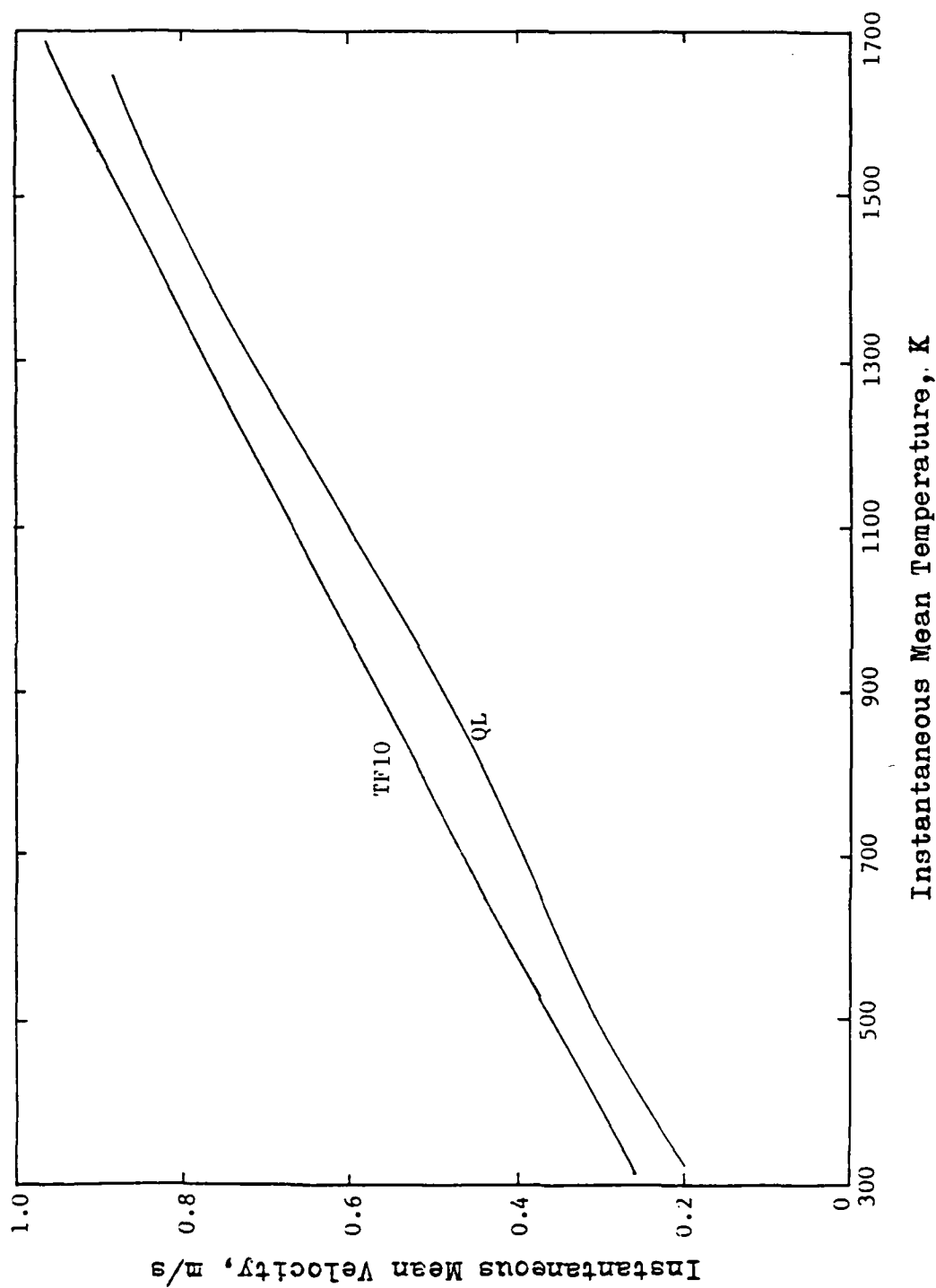


Fig. 4 Instantaneous mean velocity versus instantaneous mean temperature in methane/air V-flames. TF10, with 10-mesh turbulence grid; QL, no turbulence grid. Equivalence ratio, 0.75; mean mixture velocity, 2.4 m/s; 35mm downstream of 2.1 mm-diameter flameholder.

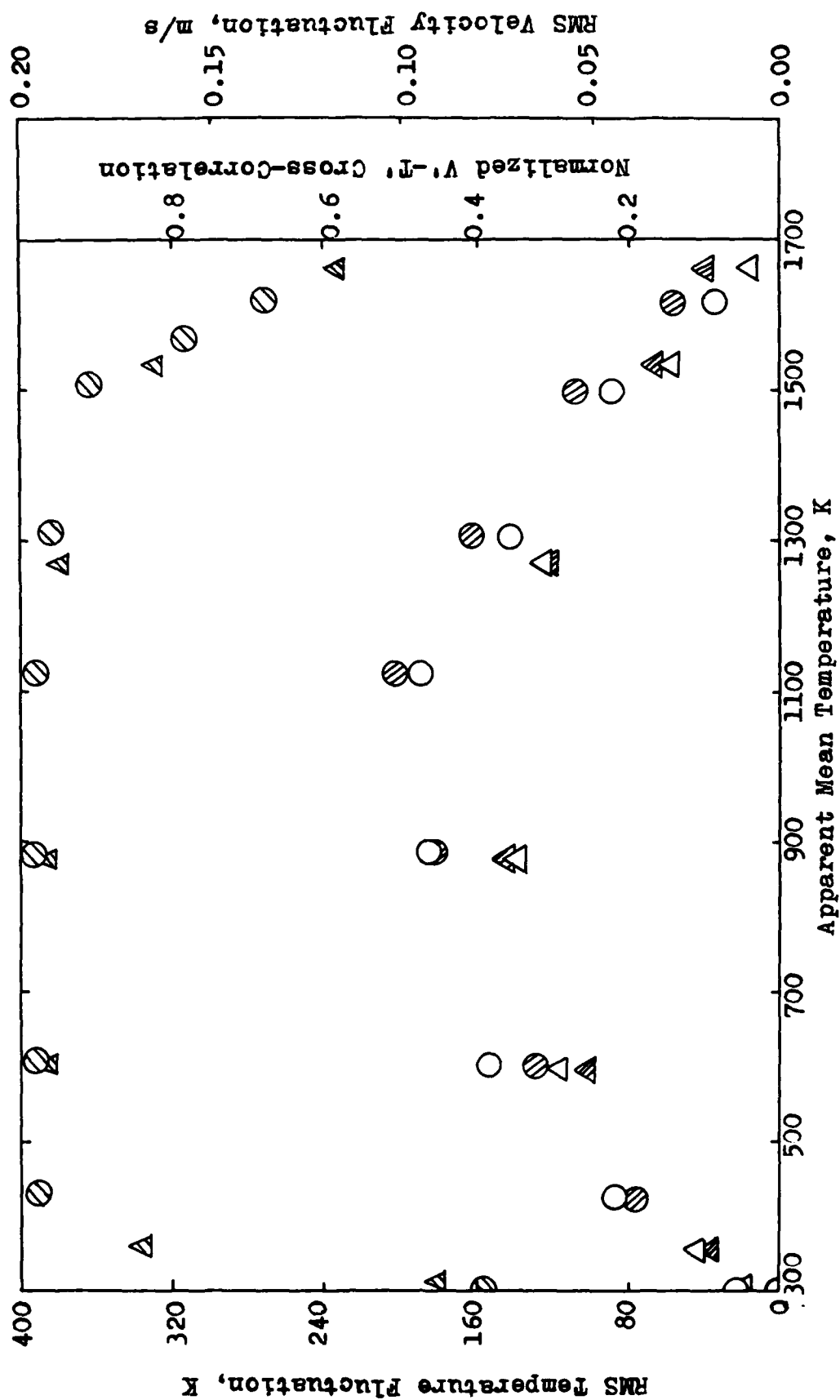
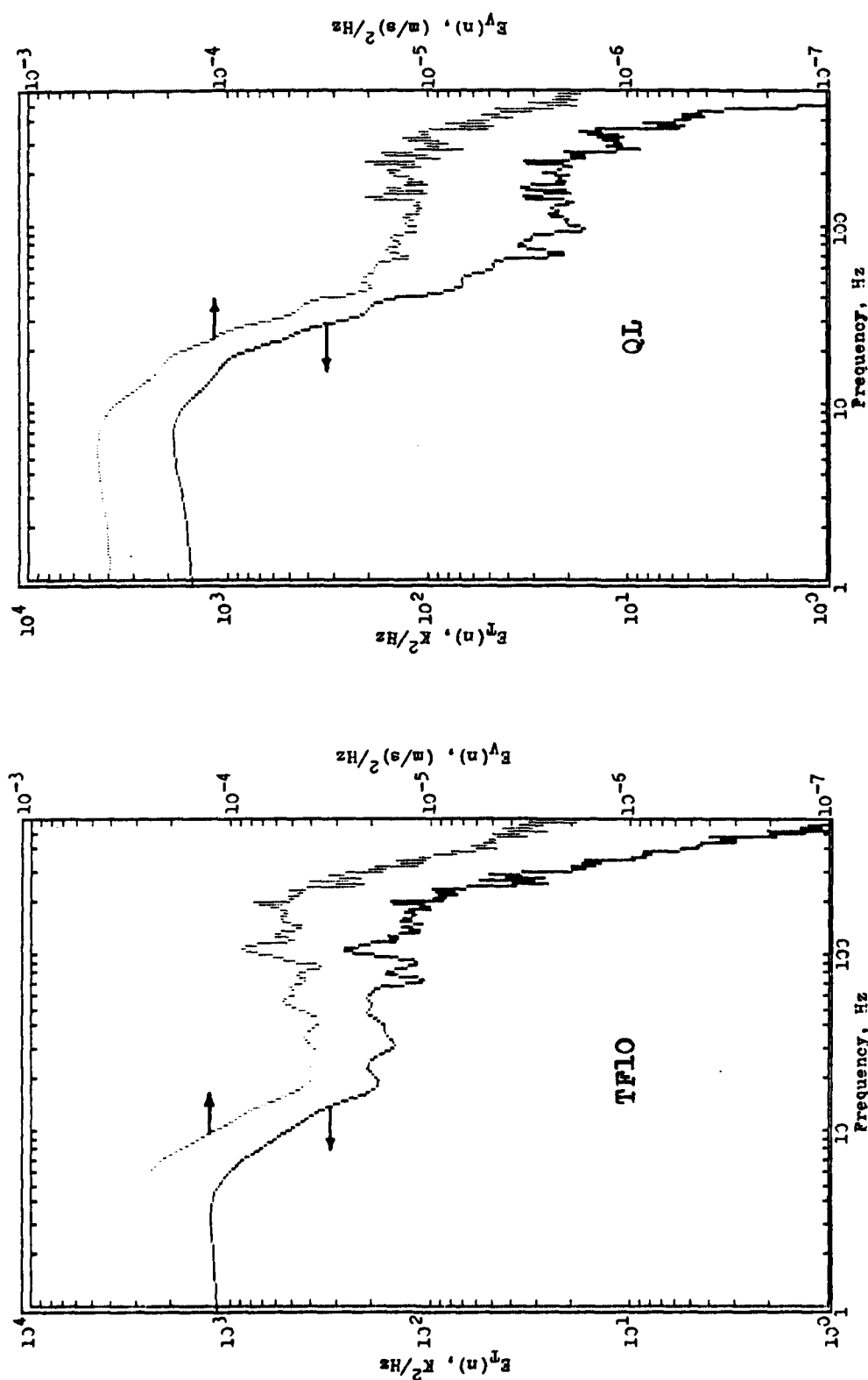


Fig. 5 Apparent low-frequency RMS temperature, RMS velocity, and normalized $V'-T'$ cross-correlation coefficient versus apparent mean temperature. Triangle, with 10-mesh turbulence grid; circle, no turbulence grid. \bigcirc , Δ RMS temperature; \bigcirc , Δ RMS velocity; \bigcirc , Δ $V'-T'$ cross-correlation.



(a)

(b)

Fig. 6 Comparison of spectral density distribution of apparent all-pass mean-square temperature (thick lines) and simultaneous velocity fluctuations (thin lines) at a position of maximum RMS values. (a) TFLO, with 10-mesh turbulence grid. (b) QL, with no turbulence grid.

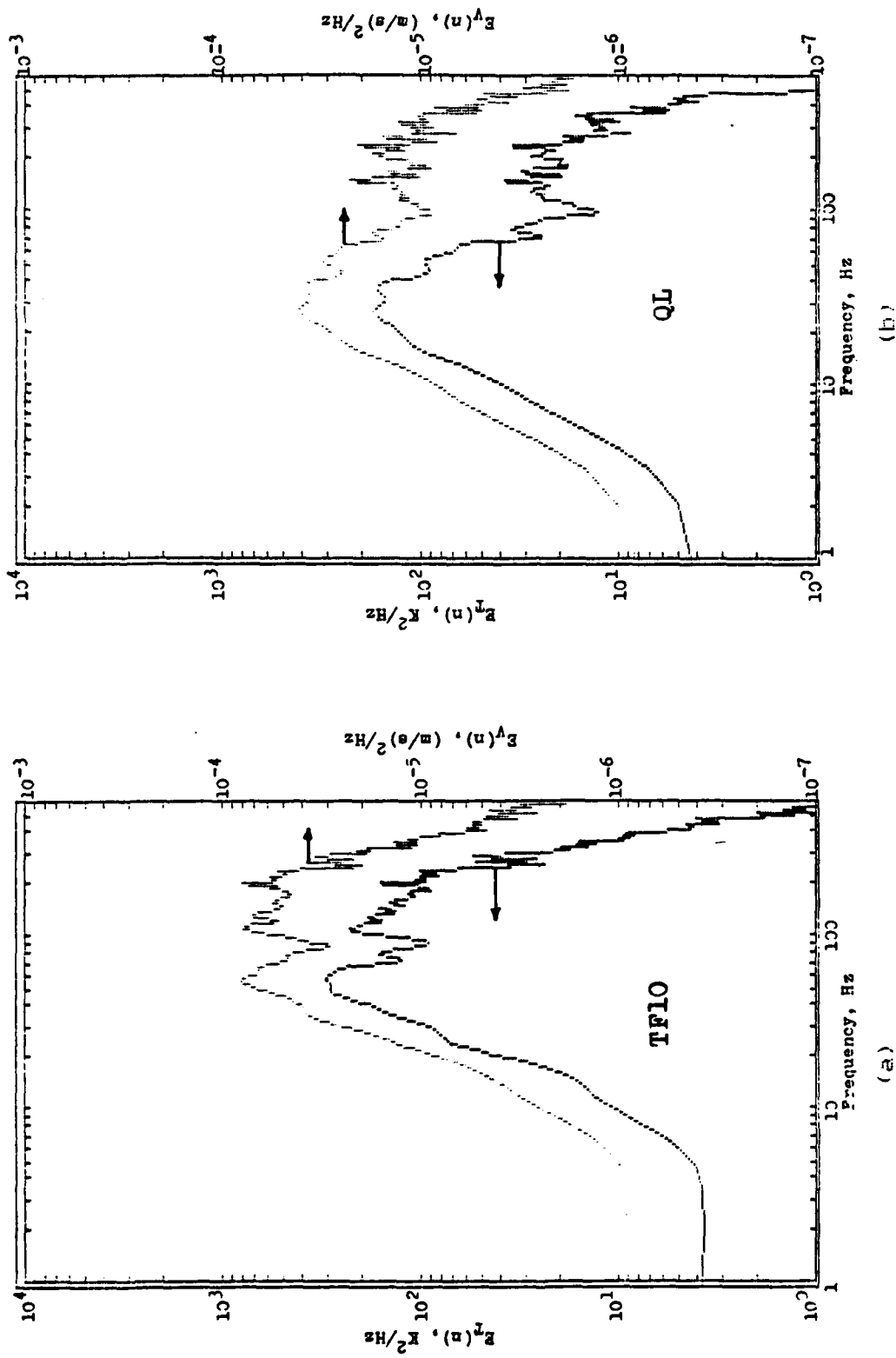
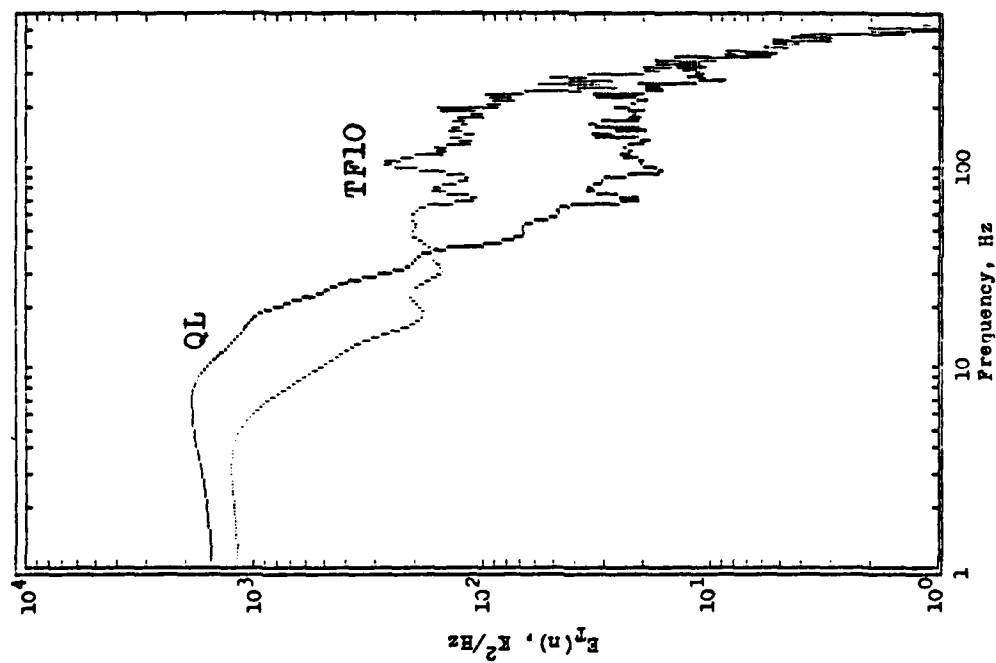
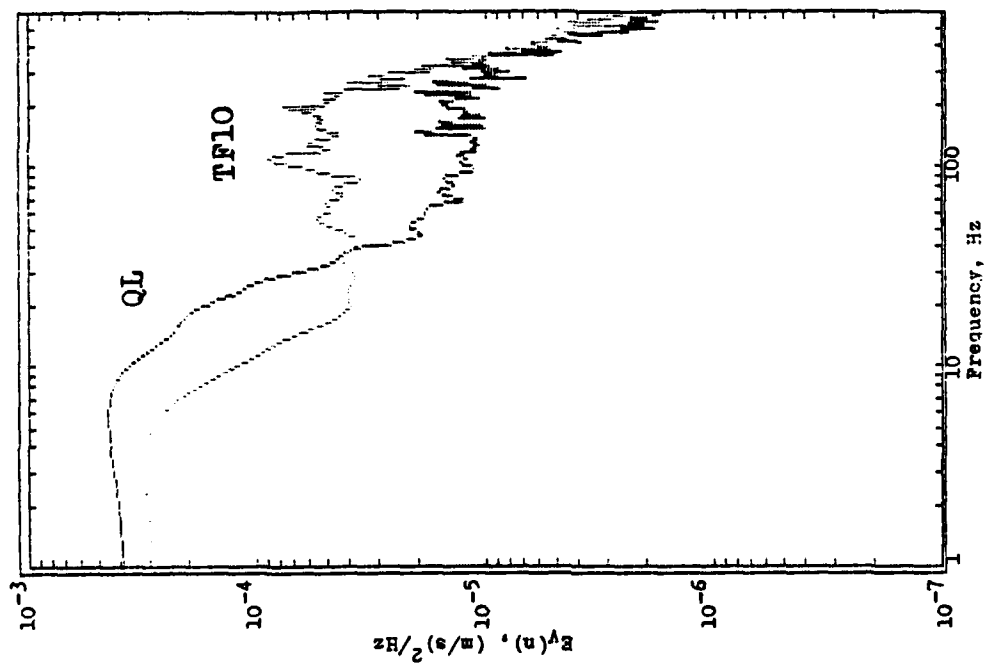


Fig. 7 Comparison of spectral density distribution of "instantaneous" high-frequency mean-square temperature (thick lines) and simultaneous velocity fluctuations (thin lines) at a position of maximum RMS values. (a) TFLO, with 10-mesh turbulence grid. (b) QL, with no turbulence grid.



(a)



(b)

Fig. 8 Comparison of spectral density distribution for TFLO, with 10-mesh turbulence grid (thin lines) and QL, without turbulence grid (thick lines) at a position of maximum RMS values. (a) apparent all-pass mean-square temperature fluctuations. (b) apparent all-pass mean square velocity fluctuations.

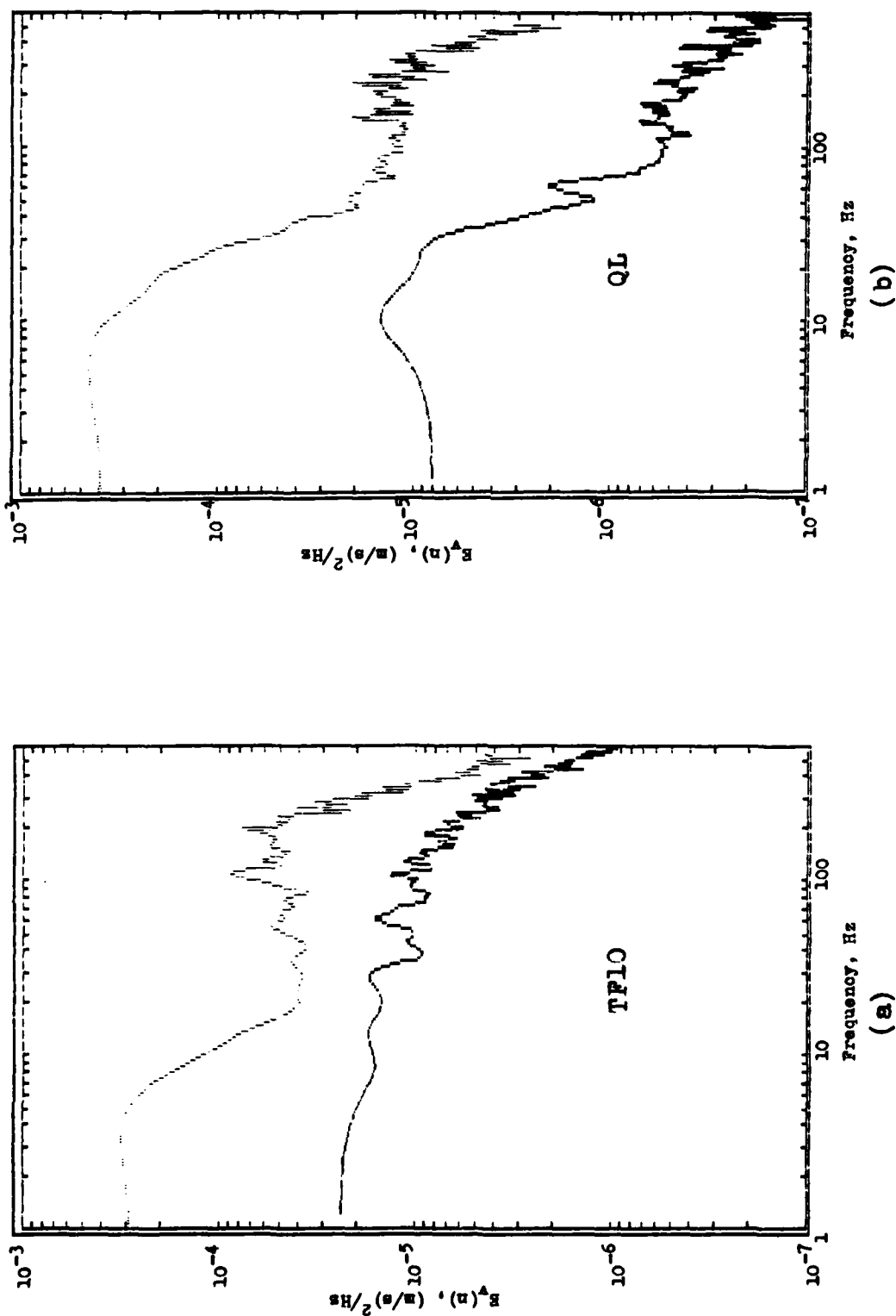
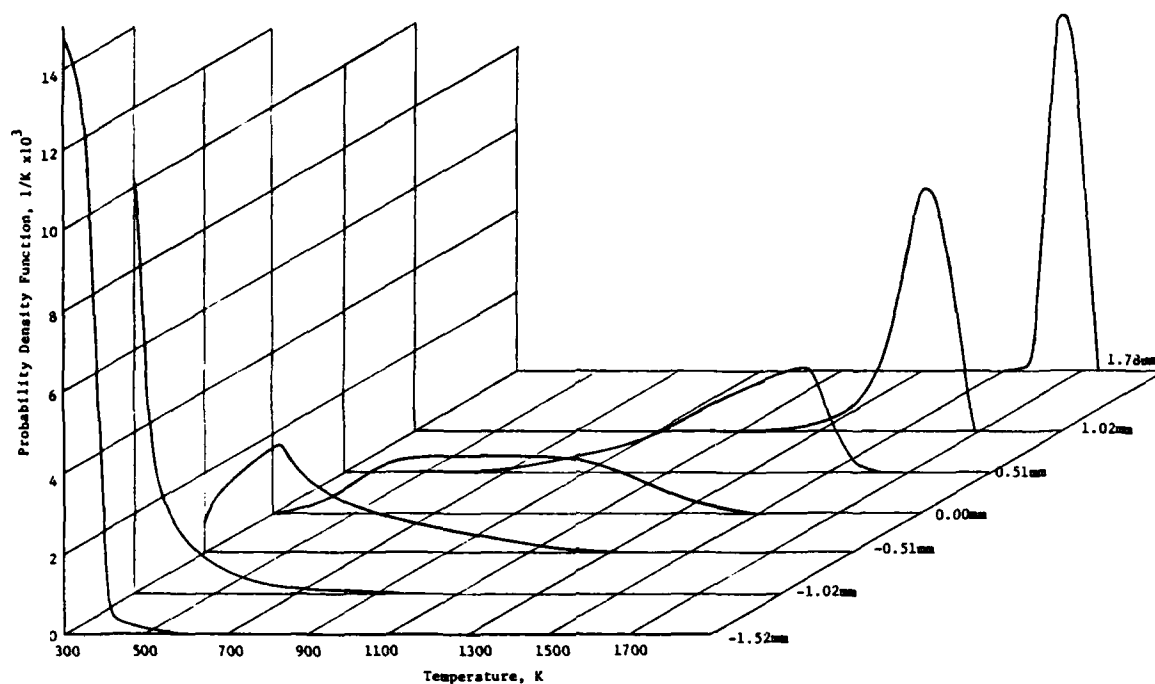
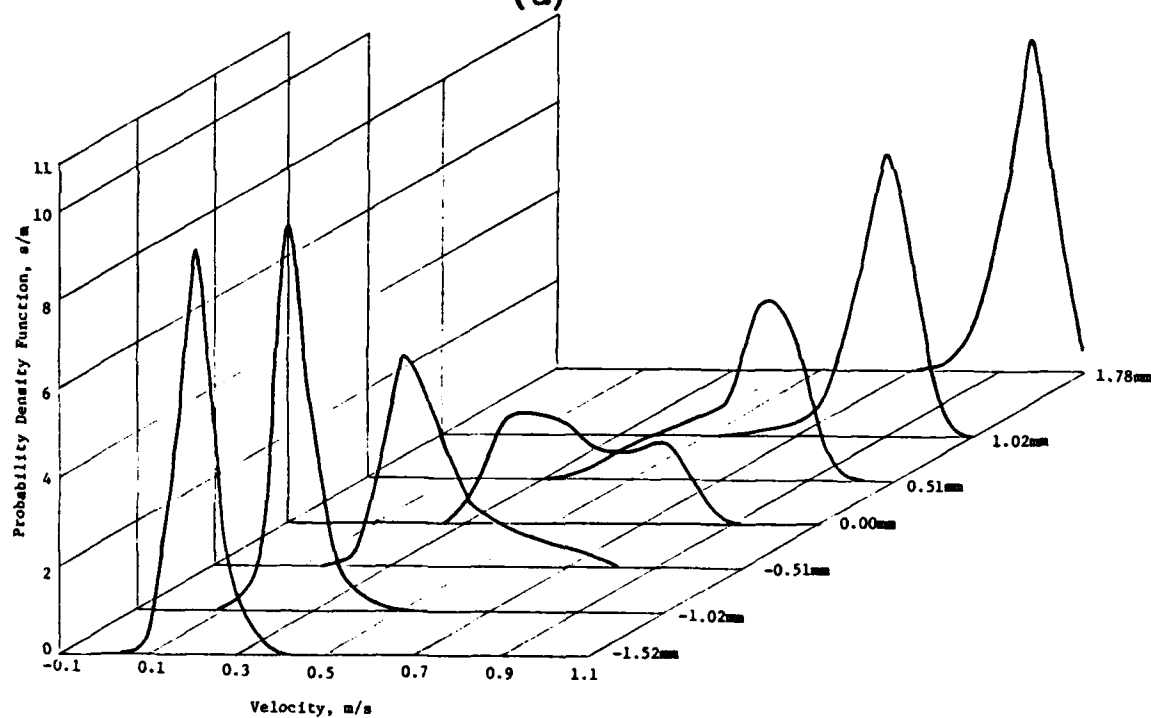


Fig. 9 Comparison of spectral density distribution of apparent all-pass mean-square velocity fluctuations just upstream of flame brush (thick line) and at a position of maximum RMS value (thin line). (a) TFLO, with 10-mesh turbulence grid, 2.5% intensity upstream, (b) QL, with no turbulence grid, 1.1% intensity upstream.

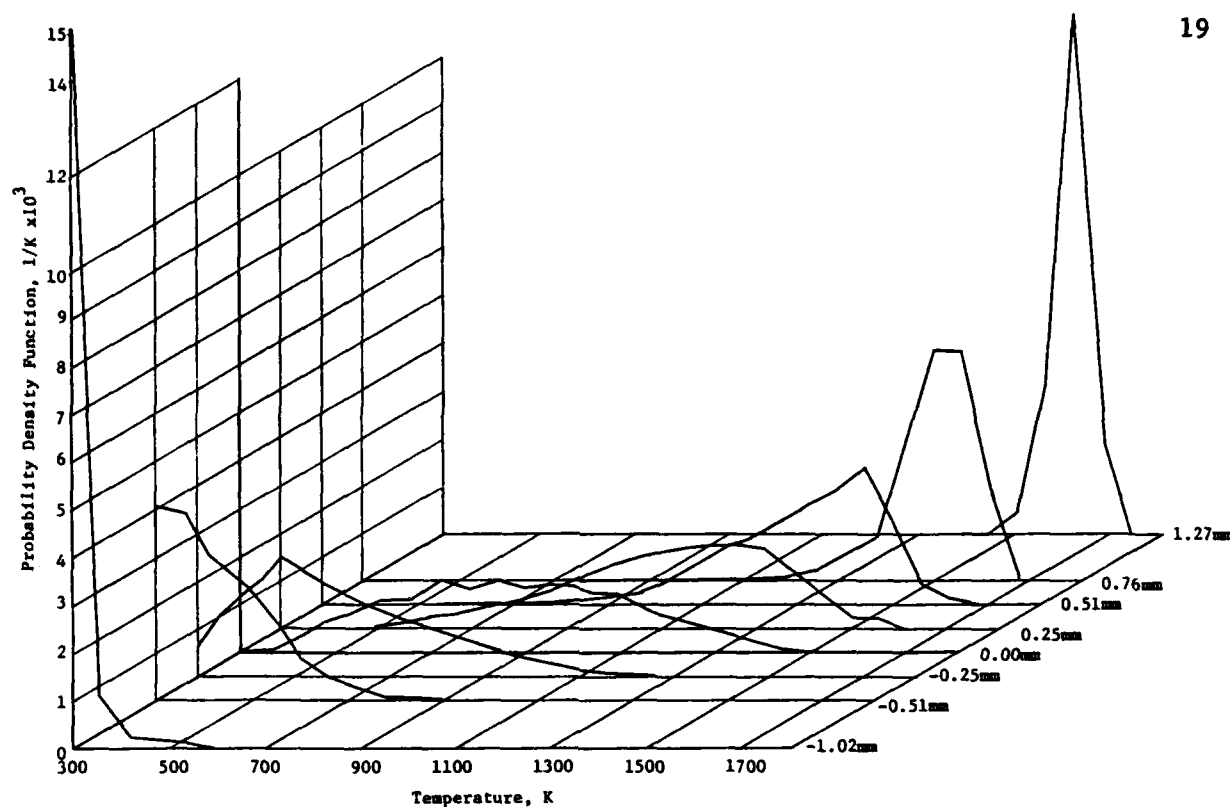


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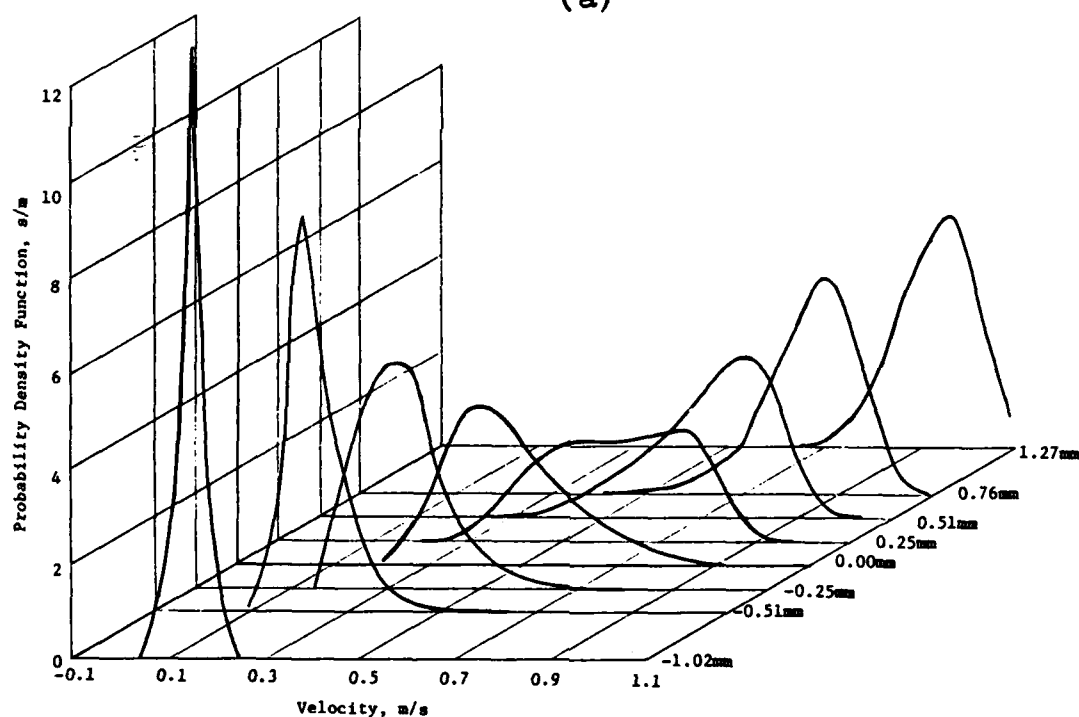


(b)

Fig.10 Probability density functions across TF10 with 10-mesh turbulence grid. Spatial coordinate with respect to location of maximum RMS values. (a) temperature (b) velocity component normal to the apparent flame brush.



(a)



(b)

Fig.11 Probability density functions across quasi-laminar flame with no turbulence grid. Spatial coordinate with respect to location of maximum RMS values. (a) temperature (b) velocity component normal to the apparent flame brush.

ENCLOSURE

Basic Instability Mechanisms
in Chemically Reacting Subsonic and Supersonic Flows
Publications and Reports
(Grant AFOSR-83-0373)

1. Abouseif, G. E., Keklak, J. A. and Toong, T. Y., "Ramjet Rumble: The Low-Frequency Instability Mechanism in Coaxial Dump Combustors", Combustion Science and Technology, 36, pp. 83-108, 1984.
2. Abouseif, G. E. and Toong, T. Y., "Theory of Unstable Two-Dimensional Detonations: Genesis of Transverse Waves", Combustion and Flame, 63, pp. 191-207, 1986.
3. Toong, T. Y. and Chang, C., "Thermal Structure of Turbulent Premixed Rod-Stabilized V-Flames", submitted for presentation at the Fall Technical Meeting, Eastern Section, Combustion Institute, 1986.
4. Toong, T. Y., "Turbulence-Combustion Interactions in Premixed Rod-Stabilized V-Flames", in preparation.

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